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The Mechanics of Episodic Tremor and Slip with Implications for Seismic Hazards in Cascadia

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Abstract

We continued development of physics-based models that explain the occurrence and characteristics of slow slip events (SSE) and are consistent with geodetic and seismic observations of Episodic Tremor and Slip (ETS) in the Pacific Northwest. In previous reports we described physics based models of SSE based on rate-state friction and dilatancy strengthening, found depth distributions of mechanical properties and pore-pressure that are consistent with the magnitude and depth extent of SSE, developed efficient algorithms for 2D and 3D quasi-dynamic boundary element modeling, and inverted for shear stress rates on the megathrust. These results showed that the shear stress rates on within the gap must decrease with time to explain the decadal-averaged deformation rates (*Bruhat and Segall*, 2016).

In northern Cascadia, kinematic inversions of GPS and tide-gauge/leveling data display an unresolved "gap" between the down-dip limit of the locked megathrust and the top of the ETS zone. Inversions of GPS and tide gauge/leveling data for shear stress rates acting on the megathrust found that a relatively deep locked zone with steep slip rate gradient at its base is required to fit the data (*Bruhat and Segall*, 2016, and report for award G14AP00038). Previous studies assumed the depth distribution of interseismic slip rate to be time invariant; however, steep slip rate gradients could also result from the up-dip propagation of slip into the locked region. During this reporting period, we investigated models where interseismic slip penetrates up-dip into the locked region, over time scales that are long compared to ETS recurrence times.

The ETS zone and gap region is modeled as a quasi-static crack driven by plate motion at the fixed down dip limit of the ETS region. Following classical crack models of faults, we present a simple model that allows crack growth over time, and derive analytical expressions for stress drop within the crack, slip and slip rate along the fault. It proves convenient to expand any non-singular slip rate distribution in a combination of Chebyshev polynomials. The inverse problem is severely under determined, as are all geodetic inversions, however the new approach allows us to

test particular cases, such as, solutions that provide bounds on the possible up dip propagation rate, or solutions that optimize inferred characteristics of the slip and stress distributions. When applied to observed deformation rates in Cascadia, best fitting models reveal that a very slow up dip propagation is consistent with the data and that the gap seems to act as a "cohesive region". A paper describing this work is now in revision at *Geophysical Journal International*.

1 Report

Crack models for penetrating creep

Like most kinematic inversions of geodetic surface rates, *Bruhat and Segall* (2016) assumed the locking depth, as well as the depth distribution of interseismic fault slip rate, to be time invariant. However, steep gradients in interseismic slip rates icould also result from the up dip propagation of slip into the locked region. Consider the interseismic slip distribution as a crack (not necessarily of constant stress) of length a driven from below by steady creep at long-term rate v^∞. Slip is defined in terms of the deep displacement $v^\infty t$, and a depth dependent function $f(z,t)$:

$$s(z,t) = f(z,t)v^\infty t. \tag{1}$$

The instantaneous slip-rate is

$$\frac{ds}{dt}(z,t) = f(z,t)v^\infty + v^\infty t\frac{\partial f}{\partial t} = f(z,t)v^\infty + v^\infty t\frac{\partial f}{\partial a}\frac{\partial a}{\partial t}. \tag{2}$$

Only if the shape function $f(z,t)$ is time invariant is the slip-rate also time invariant, $ds/dt = f(z)v^\infty$. More generally, propagation of the creeping zone, $\partial a/\partial t$, leads to an additional term in the slip-rate, which has been neglecting in kinematic slip-rate inversions.

We derive a model for deep interseismic creep as a long-term quasi-static crack driven by steady down-dip plate motion. Following classical crack models of faults, we present a simple model that allows crack growth over time, and derive analytical expressions for stress drop within the crack, slip and slip rate along the fault. Consider a 1D crack of length a, extending vertically from the free surface and loaded at constant long-term rate v^∞ at depth. In a full space, the relation between the Burger's vector distribution $B(\xi) \equiv \partial s/\partial\xi$, where s is fault slip, and the stress drop within the crack $\Delta\tau$ is

$$B(\xi) = -\frac{2}{\mu\pi}\int_{-1}^{1}\frac{\Delta\tau(u)\sqrt{1-u^2}}{(\xi-u)\sqrt{1-\xi^2}}du + \frac{2A}{a\sqrt{1-\xi^2}} \tag{3}$$

(*Bilby and Eshelby*, 1968), where A is a constant proportional to the net dislocation, and we define a normalized distance scale by $\xi = 1 - 2z/a$. Following *Bilby and Eshelby* (1968), the integration for $B(\xi)$ can be conveniently performed by decomposing the stress drop in Chebyshev polynomials of the first kind T_i

$$\Delta\tau(u) = \mu\sum_{n=0}^{\infty}\tilde{c}_i T_i(u). \tag{4}$$

Solving eq.(3) for a crack with finite stress at the crack tip (e.g., zero stress intensity, $K_{II} = 0$) and driven by steady displacement $v^\infty t$ yields

$$\Delta\tau(\xi,t) = \mu\frac{v^\infty t}{a\pi}\xi + \mu\sum_{i=2}^{\infty}\tilde{c}_i T_i(\xi) \tag{5}$$

$$B(\xi,t) = \frac{2v^\infty t}{a\pi}\sqrt{1-\xi^2} + 2\sqrt{1-\xi^2}\sum_{i=2}^{\infty}\tilde{c}_i U_{i-1}(\xi), \tag{6}$$

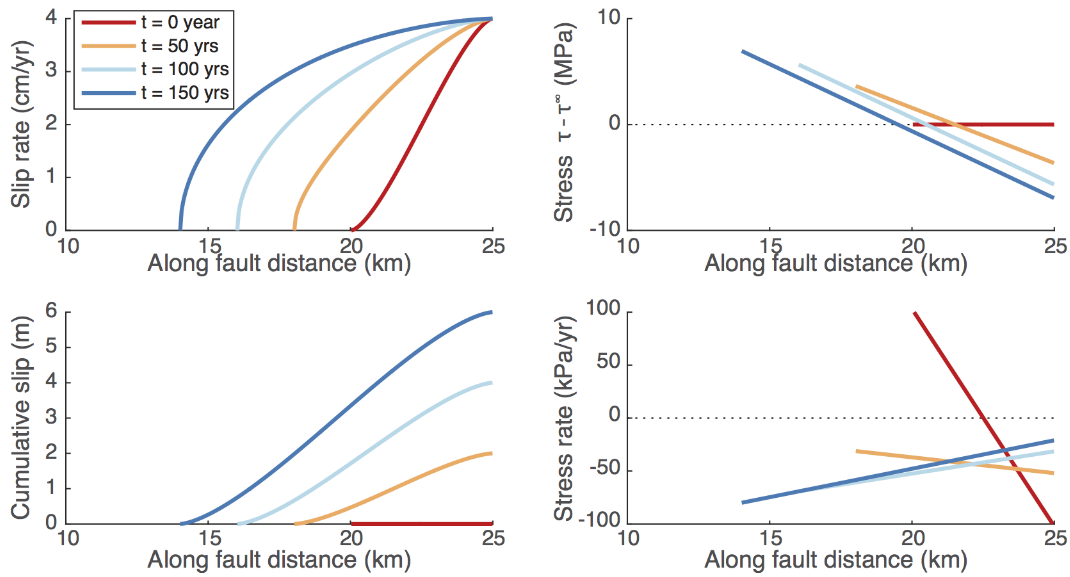

Figure 1: Slip rate, cumulative slip, stress τ - $\tau^{\infty} = -\Delta\tau$, and stress rate profiles at different times for a crack propagating upward at 40 m/year. These profiles are derived at $t = 150$ years for a crack driven by constant slip rate below z = 25 km, and all $i > 2$, $\tilde{c}_i = 0$ and $\partial\tilde{c}_i/\partial t = 0$. Slip-rate is fixed to geologic rate below z = 25 km.

where U_i are Chebyshev polynomials of the second kind. Integrating the Burger's vector distribution, to obtain the slip $s(\xi, t)$ yields

$$s(\xi,t) \quad = \quad \frac{v^{\infty}t}{\pi}\left[\xi\sqrt{1-\xi^2}+\arcsin(\xi)+\frac{\pi}{2}\right]+\frac{a}{2}\sqrt{1-\xi^2}\sum_{i=2}^{\infty}\tilde{c}_i\left[\frac{U_i(\xi)}{i+1}-\frac{U_{i-2}(\xi)}{i-1}\right]. \tag{7}$$

Taking the total derivative of $s(\xi, t)$ to get slip-rate, we find

$$\frac{ds}{dt}(\xi,t) \quad = \quad v^{\infty}g+\frac{a}{2}\sum_{i=2}^{\infty}\frac{dc_i}{dt}f_i+\frac{da}{dt}\left[g'\frac{1-\xi}{a}v^{\infty}t+\sum_{i=2}^{\infty}\frac{c_i}{2}\Big(f_i+f_i'(1-\xi)\Big)\right], \tag{8}$$

where

$$f_i \quad = \quad \sqrt{1-\xi^2}\left[\frac{U_i}{i+1}-\frac{U_{i-2}}{i-1}\right] \qquad\qquad f_i' = 2\sqrt{1-\xi^2}U_{i-1} \tag{9}$$

$$g \quad = \quad \frac{1}{\pi}\left[\xi\sqrt{1-\xi^2}+\arcsin\xi+\frac{\pi}{2}\right] \qquad\qquad g' = \frac{2}{\pi}\sqrt{1-\xi^2} \tag{10}$$

Note that using (8) one can expand any non-singular slip rate distribution in a combination of Chebyshev polynomials, with $i > 2$. Figure 1 displays slip rate, cumulative slip, stress drop $\Delta\tau$, and stress-rate profiles at different times for a crack propagating upward at 40 m/year, when we restrict analysis to the simplest case where for all $i > 2$, $\tilde{c}_i = 0$ and $\partial\tilde{c}_i/\partial t = 0$. For an immobile crack, $\dot{a} = 0$, the shape of slip rate distribution is the same as the slip profile. Allowing the crack to grow pushes the locked-creeping transition upward from 17 km to 9 km in 150 years. Over time, the slip rate profile also steepens due to the increasing contribution of the propagation term in the slip rate equation. Figure 1 also shows that, while the transition from locked to creeping fault may be abrupt *there can still be significant slip deficit below this point* as seen in the cumulative slip

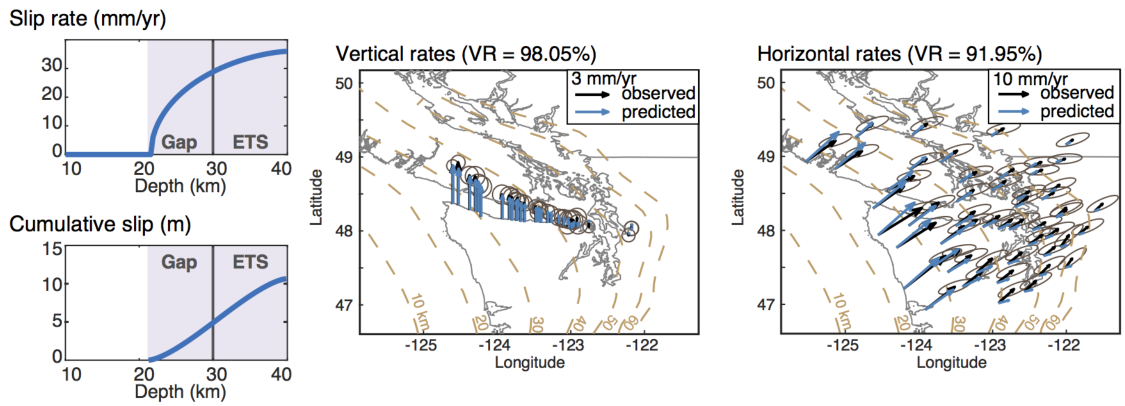

Figure 2: Best fitting model from the inversion of interseismic rates in Northern Cascadia, where the deep creeping crack migrates up dip, and all c_i and $dc_i/dt = 0$ for $i > 1$. Left: Corresponding slip rate and cumulative slip profiles. Center and right: Observed and predicted rates.

plots. This has important consequences for the slip deficit along the plate boundary, which, in the conventional framework, is solely defined by the time integral of the static slip rate distribution.

Application to Northern Cascadia

Observations of deformation rates in the Olympic Peninsula - southern Vancouver Island region include (1) velocities obtained from GPS measurements; and (2) uplift rates, determined from tide-gauge and leveling measurements. We use daily GPS positions at 51 stations from 2000 to mid 2015, from which we compute horizontal velocities averaged over numerous SSEs. We also employ decadal-averaged uplift rates from tide gauges and leveling surveys in northwest Washington from *Krogstad et al.* (2016), which we correct for postglacial rebound. Although *Bruhat and Segall* (2016) assumed the long-term rates to be statistically independent, spatial correlations are well known in geodetic data. We empirically estimate the correlations in the velocities to populate the full covariance matrix. Large correlation lengths in the horizontal GPS measurements, compared to those in the uplift rates, are inferred, which naturally decreases the weight of the GPS data in later inversions.

Accounting for penetrating creep

We apply the model for a non-singular quasi-static crack derived in the previous section to the long-term deformation rates observed in northern Cascadia. As mentioned earlier, this problem is under-determined. We thus consider end-member cases to determine the classes of models which are consistent with long-term deformation in Cascadia. Using equation (8), ds/dt is uniquely specified by: the crack length a, the loading time t, the propagation rate $\dot{a}$, the coefficients of the Chebyshev polynomials c_i and their time derivatives dc_i/dt. We employ Markov Chain Monte Carlo (MCMC) methods for inverting the deformations rates to enable the construction of posterior distributions.

Figure 2 displays the best fit for the simplest case where for all $i > 1$, $c_i = 0$ and $dc_i/dt = 0$. This simple model fits the deformation rates well, in particular the uplift rates. The inferred locking depth is 21 km, and the propagation speed is 33.4 m/yr along the fault. The inferred slip rate profile steepens rapidly in the gap. By contrast, the slip profile shows a smooth transition, leading to a very significant cumulative deep slip deficit. Posterior distributions of the up dip velocity $\dot{a}$

range rather uniformly between 30 and 120 m/year along the fault, i.e between 4 and 17 m/year in depth (assuming the fault dip is 8 degrees). As more c_i terms are added in the inversions, the up-dip propagation speed decreases to between 30 and 50 m/year along fault. These are extremely slow velocities, yet still critical to fit the data. Admissible locking depths vary from 19 to 23 km.

Stress and stress profiles that include free-surface effects

The equations relating stress drop $\Delta\tau$ and the Burger's vector distribution B derived in the first section are only strictly valid in a full space. Considering the influence of the free surface results in an additional term that prohibits an analytical solution. However, the inversions for slip rates of course use Green's functions that take into consideration the free surface. We use the inverted slip-rate distributions to compute shear stress and shear stress rate on the fault through elastic Green's functions that do account for the free surface. The advantage of the Chebyshev expansion is that it allows us to parameterize completely general, *non singular* slip-rate distributions, because the free-surface terms are non-singular, even though the full space relationship between stress and slip is incomplete.

We previously showed that forward models with rate and state dependent friction and dilatancy suggested that the net change in shear stress within the ETS zone is nearly zero; stress accumulates between SSEs, but then is relaxed during SSE (*Bruhat and Segall*, 2016). We now explore whether inversions can satisfy this observation by refining the inversion to also minimize shear stress rates within the ETS region.

We inverted for the locking depth, $\dot{a}$, and c_i, through a MCMC procedure. We assume again that the derivatives of the c_i are zeros. Solutions that respect the stress rate constraint are found for $N \geq 4$. The best fit when $N = 4$ for slip and stress rates is shown in Fig. 3, in which the locking depth is found to be 21.9 km and the propagation speed at 41.3 m/yr. The shapes of the slip and stress distributions are very similar to the best fit obtained in the previous inversion. Stress rates are negative in the gap, while nearly zero as constrained, in the ETS region. Stress is maximum at the crack tip, slowly decreases within the crack, reaching a stress drop of 1 MPa at the bottom of the ETS region. In this solution, the gap acts as a "cohesive" region, i.e. a region where stress reduces within the crack. Posterior distributions for the different parameters

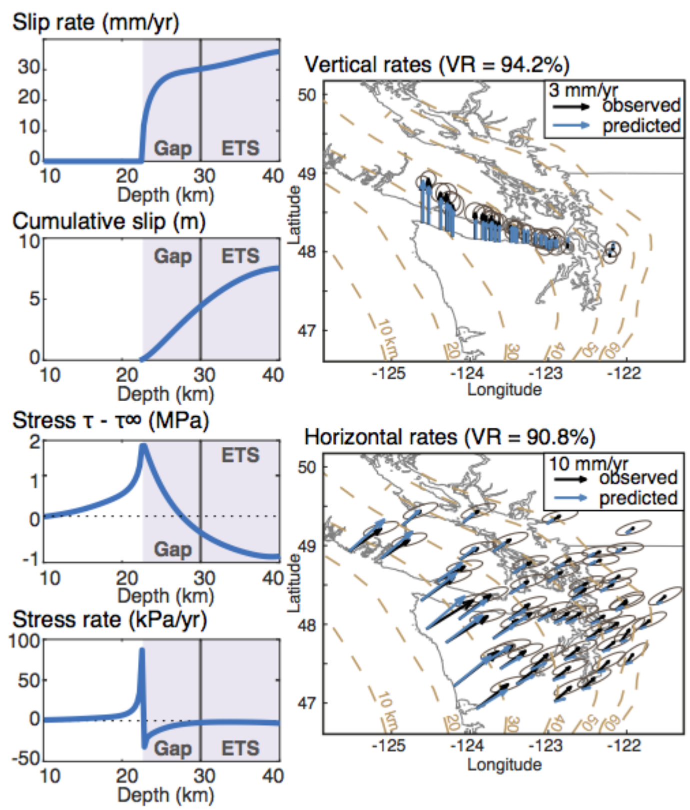

Figure 3: Best fitting model from the inversion of interseismic rates in Northern Cascadia using equations (8), where the deep creeping crack migrates up dip, and all $dc_i/dt = 0$. The Chebyshev expansion is done up to $N = 4$ and stress rate is constrained to be zero in the ETS region. Left: Corresponding slip rate, cumulative slip, stress and stress rate profiles. Right: Observed and predicted rates.

yield that admissible up dip velocities concentrated between 20 and 60 m/year along the fault. As usual, locking depths varies from 19 to 23 km.

Our data driven results provide a new class of solutions, where the locking depth migrates up dip with time. Best fitting models reveal that a very slow up dip propagation, between 30 and 120 m/yr along fault is needed to fit the data and that the gap seems to act as a cohesive region. The up dip propagation provides a solid explanation for the steep slip rate gradient at the base of the locked zone and the negative shear stress rates inferred in without requiring temporal changes of the fault strength suggested in *Bruhat and Segall* (2016) and the previous reports.

The model we describe in this report for provides a simple method for building slip and slip-rate distributions with non-singular stresses. It also establishes a bridge between purely kinematic inversions to fully physics-based models. Its simplicity allows for inversions of physical characteristics of the fault interface, which are often too computationally expensive when considering quasi-dynamic or fully dynamic simulations of earthquake cycles. On the other hand, the proposed model can be used as a guide, or as a first step before more comprehensive numerical simulations.

2 Supported bibliography

1. Bruhat, L. & P. Segall, Mechanical and Geodetic Constraints on the Gap between the Locked Zone and the ETS Region in Northern Cascadia, Abstract S33E-03 presented at 2015 Fall Meeting, AGU, San Francisco, Calif., 14-18 Dec.
2. Bruhat, L. & P. Segall, Using deformation rates in Northern Cascadia to constrain time-dependent stress- and slip-rate on the megathrust, Abstract S42A-07 presented at 2016 Fall Meeting, AGU, San Francisco, Calif., 12-16 Dec.
3. Bruhat, L. & P. Segall, Crack models to constrain time-dependent interseismic stress- and slip-rate distributions in northern Cascadia, Abstract 1110 presented at 2017 EGU General Assembly, Vienna, Austria, 23-28 Apr.
4. Bruhat, L. and P. Segall (2016), Coupling on the northern Cascadia subduction zone from geodetic measurements and physics-based models, J. Geophys. Res. Solid Earth, 121, doi:10.1002/2016JB013267.
5. Bruhat, L. and P. Segall (2017), Deformation rates in northern Cascadia consistent with slow up dip propagation of deep interseismic creep, submitted at Geophysical International Journal.

References

Bilby, B. A., and J. D. Eshelby (1968), Dislocations and the theory of fracture, in *Fracture, an advanced treatise*, pp. 99–182, Academic Press New York and London.

Bruhat, L., and P. Segall (2016), Coupling on the northern Cascadia subduction zone from geodetic measurements and physics-based models, *Journal of Geophysical Research: Solid Earth*, *121*(11), 8297–8314, doi:10.1002/2016JB013267.

Krogstad, R. D., D. A. Schmidt, R. J. Weldon, and R. J. Burgette (2016), Constraints on accumulated strain near the ETS zone along Cascadia, *Earth and Planetary Science Letters*, *439*, 109–116, doi:10.1016/j.epsl.2016.01.033.